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Hand-Held EMI Sensor Combined with Inertial Positioning for Cued UXO Discrimination

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14. ABSTRACT
The objective of this work was to combine a Small Area Inertial Measurement Tracking System (SAINT) with an advanced hand-held, time-domain electromagnetic sensor (TEM-HH) and document classification performance at the Standardized UXO Test Site at Aberdeen Proving Ground, Maryland. The TEM-HH has a single, circular, 35-cm diameter transmit coil and an inner, circular, 25-cm diameter receive coil. The SAINT integrates an inertial measurement unit and a digital magnetic compass. The two data streams were collected separately and merged during post processing. Cued data collections occurred over APG's Calibration Lanes and the Blind Grid Area at an average rate of 27 per hour. Target classification was based on a comparison of principal axis polarizabilities from a dipole fit for each anomaly to a known signature library. Our classification objectives were met; 97% of the UXO was identified as UXO (the other 3% were not detected) while rejecting 77% of the clutter.

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Acronyms

APG	Aberdeen Proving Ground
ATC	Aberdeen Test Center
ConOps	Concept of Operation
DAQ	Data Acquisition Computer
DAS	Data Analysis System
EMI	Electromagnetic Induction
GIS	Geographic Information System
GPS	Global Positioning System
IMU	Inertial Measurement Unit
IVS	Instrument Verification Strip
MTADS	Multi-sensor Towed Array Detection System
NMEA	National Marine Electronics Association
NRL	Naval Research Laboratory
POC	Point of Contact
(PTNL,)AVR	Time, Yaw, Tilt Range NMEA-0183 sentence
(PTNL,)GGK	Time, Position, Fix Quality, PDOP NMEA-0183 sentence
ROC	Receiver Operator Characteristic
RTK	Real-time Kinematic
Rx	Receive
SAINT	Small Area Inertial Navigation Tracking
SNR	Signal-to-Noise Ratio
TEM	Time-domain Electromagnetic Induction
TEMTADS	Combination of TEM with MTADS
TEM-HH	TEMTADS Hand-Held
Tx	Transmit
UTC	Universal Time Coordinated
UXO	Unexploded Ordnance

1.0 INTRODUCTION

1.1 BACKGROUND

The Hand-held EMI Sensor for Cued UXO Discrimination (TEMTADS Hand-Held or TEM-HH) is a handheld transient electromagnetic induction (EMI) sensor. This system was designed and built with funding by the Environmental Security Technology Certification Program (ESTCP) to transition the time-domain EMI sensor technology of the ESTCP Project MR-0601 5x5 towed array platform [1] to a more compact, handheld configuration for use in more limiting terrain under project MR-0807. This work was done in tandem with the development of the TEMTADS 2x2 Man-Portable Cart (MR-0909) [2], also designed with a smaller footprint than the large array for intermediate terrain conditions. Initially, both systems shared a common, backpack-carried, electronics package. The 2x2 system was upgraded from four receive coils to four three-axis receive cubes and now has a separate, larger electronics backpack.

All three TEMTADS systems have a common hardware and software heritage. The transmit pulse can be set to a variety of pulse lengths and the receive coil time gates are logarithmically spaced with a variable width setting. The measured data can be recorded over multiple transmit pulses and this output can be stacked over multiple collections for averaging. All of this is to reduce external noise and can be set in the data collection software. For a single transmit, the standard TEMTADS setting requires 2.7 seconds to record the data from a single shot. For the 2x2 with four transmits a total time of 10.8 seconds is needed and for the 5x5 array, 67.5 seconds. To make up for reduced signal in the cube receivers, the 2x2 has more recently (Camp Beale) been collecting data with additional averaging and a collection time of 64.8 seconds.

The TEM-HH sensor is shown in Figure 1-1. Unlike the 5x5 towed array and the 2x2 platform with receive cubes, it consists of only a single transmit and receive coil. This made the sensor truly "handheld" and easier to deploy in confined and rugged terrain, but requires the sensor to record more spatial measurements to make up for the lack of multiple coils. The simplest way to achieve this is by placing a gridded template on the ground. This approach was originally used with the Geonics EM61-HH and a 6 by 6 gridded template [3]. In October of 2010, the TEM-HH was demonstrated using the same template on the Standardized UXO Test Site at Aberdeen Proving Ground (APG) [4]. A photo from the demonstration is shown Figure 1-2. In terms of UXO identification and clutter rejection, its performance was comparable to the 5x5 array on the same site [5], but took longer to achieve. Each measurement on the template took 2.7 seconds and the user must position the coil head on the grid 36 times. Typically, it took five minutes to measure at each anomaly compared to the 5x5 array's time of roughly one minute. Plus, under field conditions, the template method is tedious and the user is prone to misplacing the coil on the grid requiring repeated measurements of the same anomaly.

To improve on this result, the TEM-HH was combined with the SAINT tracking system. Developed under MM-0810 [6], the "Small Area Inertial Navigation and Tracking" system can be used to track the position and orientation of a handheld sensor over a local area for up to one minute. This is sufficient to sweep the handheld coil back and forth over an anomaly 5 to 10

times covering an area comparable to the template approach. By collecting data continuously, the acquisition period is less than a minute and the data density is increased over the discretely positioned template. Figure 1-3 shows the SAINT system with the Geonics EM61-HH being demonstrated on the APG Blind Grid.

Figure 1-1 – The TEM-HH handheld sensor.

Figure 1-2 – TEM-HH and template at APG Demonstration, October, 2010.

Figure 1-3 – The SAINT system with EM61-HH at APG, July, 2009.

1.2 OBJECTIVE OF THE DEMONSTRATION

The goal of this demonstration was to repeat the Blind grid portion of the APG Standardized Test Site using the TEM-HH with the SAINT and to achieve equal or improved results in UXO characterization compared to the TEM-HH with template on the same area, but to do it in significantly less time. It should be noted that this was done as a proof-of-concept and that nothing was done to integrate or improve the two systems. The TEM-HH coil was physically attached to the end of the EM61-HH/SAINT pole. The two data streams were collected separately. A time shift parameter was added to the inversion algorithm to match the positioning data to the TEM data.

The system mobilized to the APG Standardized UXO test site in October 2012. Data collection occurred over the Calibration Lanes and the Blind Grid Area. For the Blind Grid, the union of the target lists from the previous EM61-HH/SAINT and TEMTADS 5x5 demonstrations was used as the target list. This allowed for a direct, head-to-head comparison of these results with those of the EM61-HH/SAINT configuration and comparisons with the TEMTADS 5x5 array, 2x2 array, and the TEM-HH/Template.

2.0 TECHNOLOGY

2.1 TECHNOLOGY DESCRIPTION

The TEM-HH is a single transmit/receive coil system based on the same electronics developed for the NRL TEMTADS 5x5 and 2x2 arrays. The sensor has a circular, 35-cm diameter transmit coil and an inner, circular, 25-cm diameter receive coil. Decay data are collected with a 500 kHz sample rate after turn off of the excitation pulse. These raw decay measurements are binned into logarithmically-spaced “time gates” to average out high frequency noise. Traditionally, a gate width of 5% is used. For stationary measurements, the standard TEMTADS systems use a 25 ms duration pulse, and combined with the 5% gate width, results in 120 time gates from 0.042 to 25 ms. The complete bipolar waveform is 100 ms. To further average out noise, this waveform is repeated 9 times and then "stacked" 3 times for a total duration of 2.7 seconds for each transmitter. This is too long for a system that is being swept back and forth at a speed of roughly 0.5 m/s.

Both the 2x2 array with GPS positioning and the TEM-HH with SAINT positioning are currently being used in a dynamic mode. Because of 60 Hz noise interference, the quickest data sampling rate that can be used is 1/30th of a second per measurement. With no repetitions or stacking, the longest, bipolar pulse duration possible is 8.33 ms. With 3 repetitions, a pulse duration of 2.77 ms is possible. To make up for the lack of averaging, the dynamic systems are being used with wider gate widths, typically 20 or 30%. At 30% for the 2.77 pulse, this results in 19 gates. The first four are dropped because of transmit turn-off ringing, resulting in 15 time gates from 0.11 to 2.5 ms. This setting has been tested on the TEM-HH and found to give adequate SNR for the typical range of UXO sizes and depths.

The SAINT system is contained in a triangular, yellow case that attaches to the pole of an EM61-HH. For this test, the EM61-HH coil has been removed and replaced by the TEM-HH coil (see Figure 2-1). The TEM-HH coil has been carefully positioned to have the same center as the EM61-HH. The yellow case contains an inertial measurement unit (IMU) and an embedded data acquisition computer. An external battery supplies power. The system automatically boots up and provides user prompts and control through several LED's, an audible beep, and a single switch. The IMU data for each data collection is saved to an SD memory card and downloaded to a PC computer later. The IMU data is post-processed on the PC computer to give the EMI coil trajectory. There has been no effort to integrate the TEM and SAINT data streams. Each is collected separately with no common time stamp. The TEM data and the IMU position data are matched up in time with a time shift parameter in the inversion algorithm.

Figure 2-1– The TEM-HH attached to SAINT at APG, October, 2012.

3.0 PERFORMANCE OBJECTIVES

Table 3-1 – Performance Objectives for this Demonstration

Performance Objective	Metric	Data Required	Success Criteria	Results
Quantitative Performance Objectives				
Instrument Verification Strip (IVS) Results	Reproducibility of inversion results over a common set of objects	Daily measurement of IVS items	≤ 20% RMS variation of fit polarization amplitudes and fit depth	Achieved
Correct classification of targets of interest	Number of targets of interest identified	• Prioritized dig list • Scoring report from APG	95% correct identification of all targets of interest	97% of All UXO identified as UXO (3% Not Detected)
Reduction of False Alarms	Number of false alarms eliminated	• Prioritized dig list • Scoring report from APG	Reduction of false alarms by 50% or more with 95% correct identification of munitions	Achieved 77% Rejected
Cued Production Rate	Number of cued targets investigated per day	Log of field work	1 minute measuring each anomaly. 150 anomalies per day	Achieved
Analysis Time	Average time required for inversion and classification	Log of analysis work	< 5 min per target	Not Met, but Achievable
Qualitative Performance Objectives				
Ease of Use	System can be used in the field without significant issues	Feedback from field team	No negative comments on ergonomics or ConOps	Minor improvements in ergonomics and ConOps possible
Reliability	• Number of operational hours recorded per day • Number of significant technical issues	• Field logs of operational hours per day • Field logs of significant technical issues	• ≥ 6 hrs/day • ≤ 1 significant technical issue per day	• 1 significant problem delayed work by 1.5 days • After that, Achieved

3.1 INSTRUMENT VERIFICATION STRIP

To document consistent sensor response and inversion results to a common set of objects, an Instrument Verification Strip (IVS) was set up and measured each morning and at the end of the day. The sand pit at APG was used. A 37mm and 25mm were buried roughly 0.30 m deep and remained in place for the entire test. Both items were horizontal, but the 25mm was oriented North-South and the 37mm was East-West. Flags were placed and used to return the SAINT tripod to roughly the same position and height for each measurement.

3.1.1 Metric

The metric for the IVS was reproducible signals and inversion results from the items in the IVS.

3.1.2 Data Requirements

Measure the IVS items every morning and at the end of the day.

3.1.3 Success Criteria

Variability of the inverted polarizations is less than 20% of their mean amplitude. The fit depth relative to the local tripod height varies less than 20%.

3.1.4 Results

Success was achieved for this criterion. All fit depths were within 6% of their average depth. All inverted polarizations were within 20% of their mean amplitude. These results are discussed further in Section 7.1.

3.2 CORRECT CLASSIFICATION OF TARGETS OF INTEREST

This is one of the two primary measures of the classification value of this sensor. Our goal was to properly classify a large percentage of the seeded munitions items. By collecting high-quality, precisely-located data, we expected to be able to discriminate munitions from scrap and frag with reasonable efficiency.

3.2.1 Metric

At a seeded test site such as the APG standardized test site, the metric for classification efficiency is straightforward. We prepared a ranked dig list from the survey data with a UXO / Clutter decision for each Blind Grid cell and ATC personnel used their scoring algorithms to assess our results.

3.2.2 Data Requirements

The identification of most of the items in the test field is known to the test site operators. Our ranked dig list is the input for this metric and ATC's standard scoring is the output.

3.2.3 Success Criteria

The objective is considered met if more than 95% of the seeded munitions items were correctly classified.

3.2.4 Results

This criterion was met; 97% of the UXO was identified as UXO. The other 3% were not detected. Results of the APG scoring are presented in Section 7.2 and compared to the other TEM systems.

3.3 OBJECTIVE: REDUCTION OF FALSE ALARMS

This is one of the two primary measures of the classification value of this technology. We expect to properly classify a large percentage of the clutter as such. By collecting high-quality, precisely-located data, we expect to be able to discriminate munitions from scrap and frag with some efficiency.

3.3.1 Metric

At a seeded test site such as the APG standardized test site, the metric for false alarm elimination is straightforward. We prepared a ranked dig list for the interrogated Blind Grid cells where we indicated a UXO / Clutter decision for each cell and ATC personnel used their automated scoring algorithms to assess our results.

3.3.2 Data Requirements

The identification of most of the items in the test field is known to the test site operators. Our ranked dig list is the input for this metric and ATC's standard scoring is the output.

3.3.3 Success Criteria

The objective is considered met if more than 50% of the non-munitions items were labeled as no-dig while retaining 95% of the munitions items on the dig list.

3.3.4 Results

This criterion was met; 77% of the clutter was rejected. Results of the APG scoring are presented in Section 7.3 and compared to the other TEM systems.

3.4 OBJECTIVE: CUED PRODUCTION RATE

Even if the performance of the technology on the metrics above is satisfactory, there is an economic metric to consider. Survey efficiency is the metric that was tracked in this demonstration.

3.4.1 Metric

For cued data collection, the metric is the number of anomalies investigated per day. Combined with the daily operating cost of the technology this gives the per-anomaly cost.

3.4.2 Data Requirements

Productivity was determined from a review of the demonstration field logs.

3.4.3 Success Criteria

This objective was considered met if the production rate was at least 150 anomalies per day. Previously with the TEM-HH and the template, the goal was 50 targets a day and an average rate of 67 per day was achieved.

3.4.4 Results

This criterion was met. On one good day, over 200 flags were measured in an 8 hour day. This is further discussed in Section 7.4.

3.5 OBJECTIVE: ANALYSIS TIME

The other component of system costs is the amount of analyst time required for data analysis. We tracked the near-real-time analysis time in this demonstration.

3.5.1 Metric

The time required for inversion and classification per anomaly is the metric for this objective

3.5.2 Data Requirements

Analysis time was determined from a review of the data analysis logs.

3.5.3 Success Criteria

For this demonstration, the objective was considered met if the average inversion and classification time is less than 5 min. The CPU time for processing is on the order of one minute and for the bulk of the data collected is automated. The analysts reviewed standard diagnostic plots and decided if fixes and/or retakes were necessary.

3.5.4 Results

An automated routine was written prior to the APG test. It read in the two data streams. The analyst clicked on an interactive plot to roughly line up the two data sets in time and selected a region of data for zeroing the background. The inversion would then run and dump out a set of data quality plots for the analyst to review. This was accomplished in roughly 5 minutes.

On site several unanticipated problems arose. One problem in the data was not found until after the demonstration was over. The total time spent per each anomaly was a great deal more than 5 minutes. This is discussed further in Sections 6.1 and 7.5.

3.6 OBJECTIVE: EASE OF USE

This objective represents an opportunity for all parties involved in the data collection process, especially the data collection team, to provide feedback in areas where the process could be improved.

3.6.1 Data Requirements

Discussions with the entire field team and other observations were used.

3.6.2 Results

Overall, the system was easy to operate. Some minor ergonomic improvements could be made and are discussed in Section 7.6.

3.7 OBJECTIVE: RELIABILITY

This objective captures the readiness of the system for live site demonstrations as an integrated system.

3.7.1 Data Requirements

The number of operational hours per day and the frequency of significant technical issues was determined from a review of the demonstration field logs.

3.7.2 Results

After the initial problems with the electronics were fixed, the system worked reliably. If some effort could be put into integrating the two data streams, the system could be fielded for a live site demonstration. This is further discussed with other recommended improvements in Section 0.

4.0 SITE DESCRIPTION

The Standardized UXO Technology Demonstration Sites Program is a multi-agency program spearheaded by the U.S. Army Environmental Command (USAEC). The U.S. Army Aberdeen Test Center (ATC) and the U.S. Army Corps of Engineers Engineer Research and Development Center (ERDC) provide programmatic support. The program is being funded and supported by the Environmental Security Technology Certification Program (ESTCP), the Strategic Environmental Research and Development Program (SERDP), and the Army Environmental Quality Technology (EQT) program. Further information can be found on their web site, http://aec.army.mil/usaec/technology/uxo01.html, and in the reference [7].

The TEM-HH/SAINT system was taken to the Standardized UXO Test Site at Aberdeen Proving Ground. There are a variety of test scenarios at the APG test site. Because it is a cued system, the Calibration and Blind grids were measured by the system. These grids are laid out in regular square cells, and the center of each cell is flagged. Ground truth is provided for the Calibration grid which contains multiple examples for the targets-of-interest (TOI) in the Blind grid. Measurements from the Blind grid are analyzed to create a ranked target list. The target list is independently graded by the site sponsors. A map of the test site is shown in Figure 4-1.

4.1 SITE SELECTION

APG has been used as the site of the first field demonstration for each of the TEMTADS technologies: the 5X5 array, the 2X2 array, and the TEM-HH with template. This allows to current TEM-HH/SAINT system to be compared to past results. The APG site is located close to our base of operations in northern Virginia and southern Maryland and therefore minimizes the logistics costs of deployment. Use of this site allows us to receive validation results from near-real-world conditions without incurring the logistics and intrusive investigation expenses that would be required for a demonstration at a live site.

4.2 SITE HISTORY

The Standardized UXO Test Site is adjacent to the Trench Warfare facility at the Aberdeen Proving Ground. The specific area was used for a variety of ordnance tests over the years. The area was extensively surveyed and cleaned up prior to the emplacement of the original test items. The test site has been reconfigured twice over the years, and unexplained anomalies identified by demonstrators using the site have been investigated and removed. In the current configuration, there are still a number of small, not emplaced anomalies scattered across the Calibration and Blind grids.

4.3 SITE GEOLOGY

Detailed geologic information can be found in APG test site reports [7]. The TEM sensors measure only a weak magnetic susceptibility response from the soil; on the order of several milli-volt or less in the time gates used at nominal sensors heights. The Calibration and Blind

grids are relatively flat. There are some ruts and depressions where the ground has settled from emplacement of targets and where water tends to collect. This provided moderate challenge to the footing of the operator sweeping the TEM-HH.

4.4 MUNITIONS CONTAMINATION

As noted in the references [7], the site has been put to a variety of UXO related uses and was extensively covered with UXO debris. It has been cleaned and re-cleaned several times as a test site.

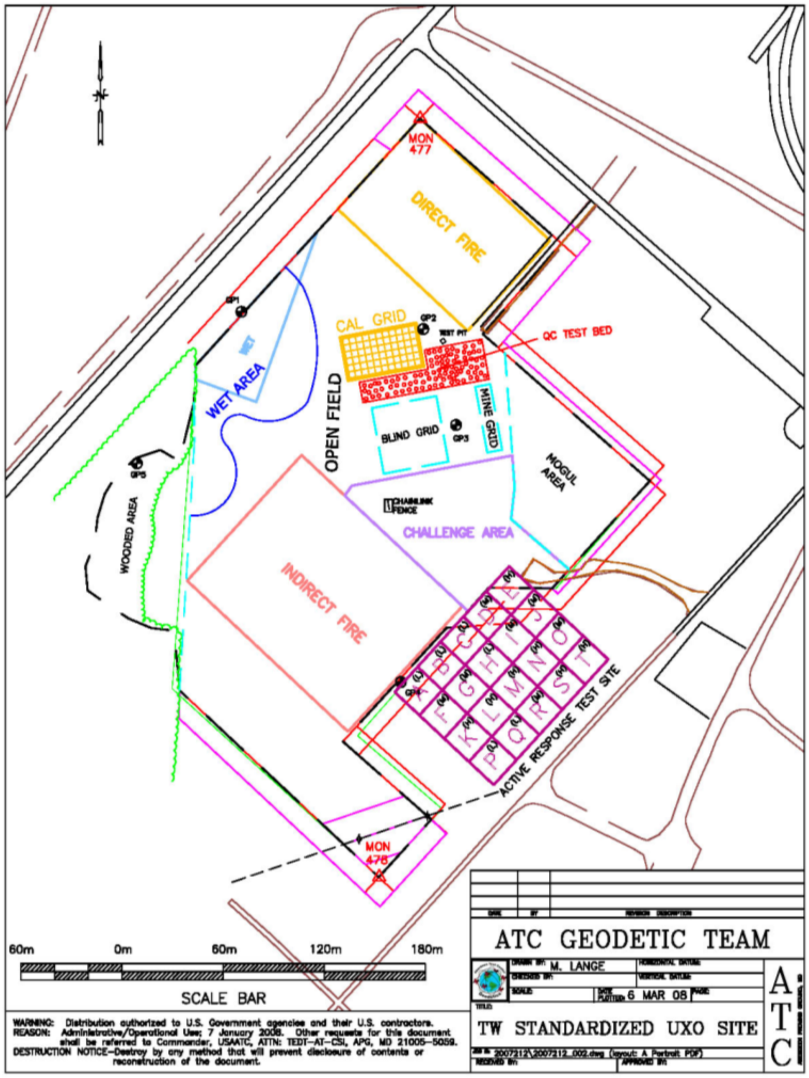

Figure 4-1 – The APG Standardized UXO Test Site

5.0 TEST DESIGN

5.1 CONCEPTUAL EXPERIMENTAL DESIGN

The TEM-HH/SAINT system was made for cued measurements, and the objective of the APG demonstration was to show that it can perform as well as the other TEM cued systems in identifying buried UXO. To allow for a head-to-head comparison, the system visited the union of all Blind grid targets visited previously by the TEM 5X5, the TEM-HH with template, and the EM61-HH/SAINT. At each flag location, the system was swept side-to-side to cover an area comparable to the wooden template previously used with the TEM-HH.

5.2 SITE PREPARATION

The APG test site is maintained by onsite personnel. The site was mown and flagged prior to our arrival. A field building with electricity and other amenities is provided. This building stored the equipment, charged batteries, allowed the analyst to work and field operators to take a break and shelter from the elements.

5.3 SYSTEM SPECIFICATION

The TEM-HH system consists of the single coil head, the backpack with electronics and batteries, and a wireless tablet computer to control the system. The SAINT system consists of an embedded acquisition computer and an IMU contained in a weather proof enclosure with control lights and buttons. The SAINT is powered by an external PC laptop battery. The TEM-HH coil head and the SAINT enclosure are attached to a pole that can be swept by an operator.

The TEM-HH is based on the same electronics and software as the other TEMTADS systems. The primary difference is that it collects data with the coil in motion. To do this, the acquisition software is set to take data at its highest data rate with reduced averaging, a shorter pulse duration, and fewer time gates. The total transmit waveform (and data rate) is 1/30th of a second. The pulse on and off duration is 2.77 msec, allowing for 3 repetitions of the bipolar waveform in 1/30th of a second. Time gates are spaced logarithmically with the width increasing as a percentage of the time gate value. To provide more averaging of high frequency noise, this percentage width was set to 30% for the moving system. This results in 19 time gates over the 2.77 msec transmit off time. The coil head is swept at speeds of 0.5 to 1.0 m/s. At the data acquisition rate, this results in data samples every couple of centimeters. The operator makes eight passes back and forth over the flag area. Each pass is roughly 0.10 to 0.15 m apart.

The SAINT system works by starting and stopping on a tripod to zero out the drift and bias of the inertial motion sensor. At each flagged anomaly, the tripod was placed roughly 1.5 to 2 meters off to the side. The TEM-HH/SAINT system was started and collected 15 seconds of stationary data (called a "zero velocity update"). The operator then lifted the system and swept it back and forth over the flag area for 30 seconds. The system was returned to the tripod for another 15 seconds. Data acquisition was then stopped. The total data recording time should be one minute. The tripod and system were then moved to the next flagged anomaly. Total time

spent per anomaly was less than two minutes. The IMU sampled accelerations and angular rates 600 times a second. This data was post-processed on a PC to provide the 3D trajectory (position and orientation) of the coil head at an equal rate.

5.4 CALIBRATION ACTIVITIES

The complete APG Calibration grid was measured and processed as a check on the data and as a source for the polarizations of TOI's in the Blind grid. Because the moving TEM-HH uses a shorter pulse, the polarization library for the longer pulse, previous TEMTADS systems could not be used.

As a further check on reproducibility, an Instrument Verification Strip was set up by burying a 37mm and a 25mm in the available sand, test pit area. The items and their depths were selected to provide signals with peak SNR amplitude greater than 10. Many of the TOI's in the Calibration grid are of lower SNR. Typically noise levels are on the order of 0.2 to 1.0 mV. The IVS items were measured at the start and end of every day. The inverted polarizations should vary no more than 20% of their average value. The inverted "depths" are relative to the local SAINT coordinate system which is determined by tripod placement. For the IVS measurements, the tripod was setup in the same spot every day. The variation in these inverted depths should vary by no more than 20%. The 20% criterion was based on test measurements made on a 4" diameter aluminum sphere. The sphere was measured ten separate times and a variation in polarization amplitude and fit depth on the order of 20% was observed. This variability is greater than with the stationary systems and is most likely due to the small positioning errors of the SAINT system.

5.5 DATA COLLECTION

Overall, 66 Calibration grid, 298 Blind grid, and 14 IVS measurements were made in the course of a little over 2 days. The first day and a half was spent finding, diagnosing, and fixing an unexpected problem in the TEM-HH data acquisition computer. A total of 4 days was spent onsite.

For the APG demonstration, there were two operators and an analyst. One operator wore the backpack and swept the system back and forth over the flag location. This operator started and stopped the SAINT acquisition. The second operator controlled the TEM-HH acquisition from the wireless tablet computer. Because there was no synchronization between the two systems, the operator's would start them at roughly the same time. The second operator kept notes on the process and assisted in moving the SAINT tripod from flag to flag.

Data was downloaded roughly every hour (about 20 flags). The SAINT was plugged into a USB port on the TEM-HH acquisition PC. The embedded SAINT computer would emulate a USB memory key and the raw binary data files (one per flag) were copied off. These files plus the TEM-HH files (also one per flag) were then copied to an actual USB key and passed to the data analyst for processing. Data was downloaded 3-4 times in the morning, 3-4 times in the afternoon with an hour break for lunch. Batteries were typically swapped out first thing in the

morning and then again at lunch; the battery for the TEM computer was hot-swapped slightly more often. The SAINT battery was often good for the entire day.

The analyst processed the SAINT files into position information and then ran a quick data quality and inversion routine. Typically, he had a list of re-do's from the morning data ready by early afternoon and a list of afternoon re-do's ready by the next day. For each flag, there was a plot of the SAINT measured trajectory, a plot of the TEM-HH transmit current, and a plot of the TEM-HH data versus the inverted, model fit. From these plots, the analyst decided if the data was good or required re-measuring.

Figure 5-1 shows a sample data quality plot from the 37mm in the IVS. The top plot shows the time series of the TEM-HH data used in the inversion (black curve and symbols) along with the inversion result (red curve). The bottom left plot is a contour of the mapped data (data black, model red). The gray trajectory is from the processed SAINT measurement. The gray symbols are the TEM-HH data positions mapped to the SAINT times. The bottom right plot shows the inverted polarizations and the model parameters and fit quality are printed to the right.

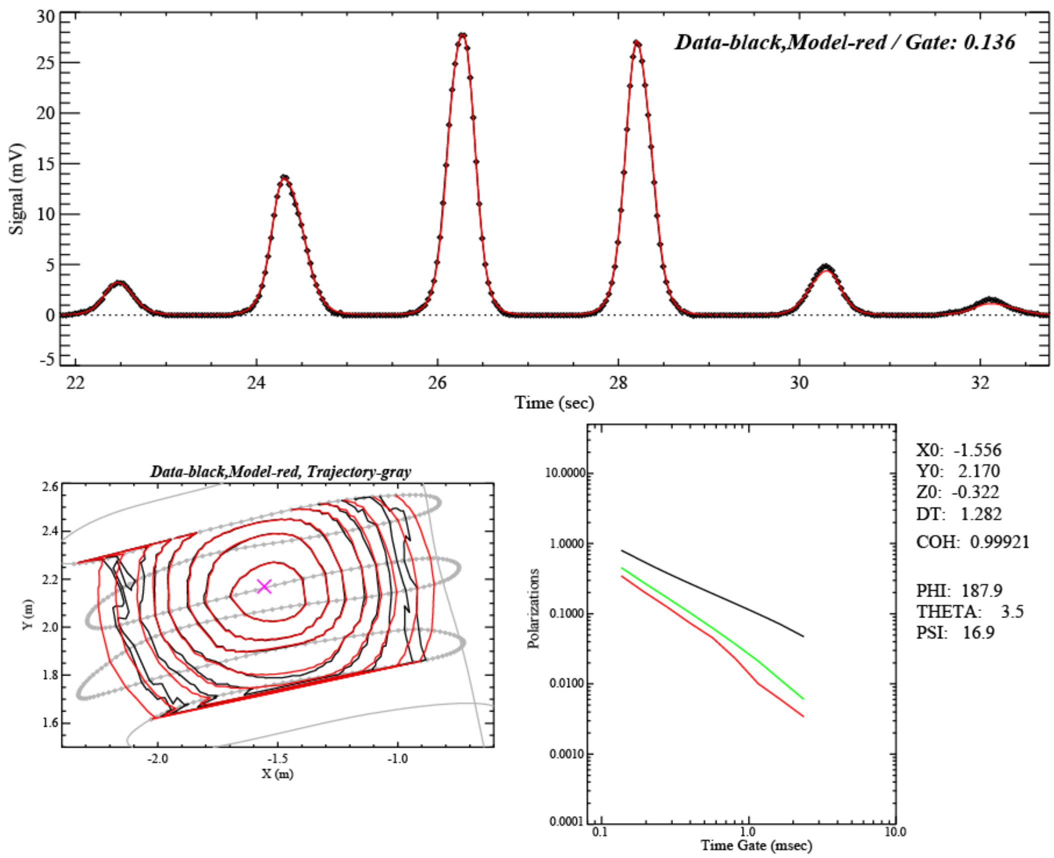

Figure 5-1 – Sample data quality plot of SAINT mapped TEM-HH data and inversion result. Data is from 37mm in IVS.

Raw data is stored in binary files on each system with an identifying number in the file name. Because the two sensors collect data separately, the number systems are not matched. The file numbers and which flags they belong to was tracked in log books kept by the operators and analyst. The SAINT data was post-processed into an ASCII file with the positioning information. The TEM-HH data was exported into an Excel CSV file. Both files retained the original identifying number in their name. Data processing and inversion results were done in an analysis package called IDL. The final results (raw data, processed data, and inversion results) from each flagged location were saved to a binary "save set" that can be read by this software. These files were named by the APG location id, the SAINT file number, and the TEM-HH file number.

5.6 VALIDATION

Validation for the Calibration grid is provided by the known ground truth. Validation for the Blind grid is provided by the target list graded by the test site operators who retain the ground truth.

6.0 DATA ANALYSIS

6.1 APG DATA PREPROCESSING

To invert the TEM-HH data, the region of signal data needs to be selected out and background levels need to be subtracted off. No significant soil background response was observed at APG or the Blossom Point test site. If significant soil response levels and/or variability are observed in the data, the coil can be raised higher above the ground as it is swept.

From file to file, the DC levels of the TEM-HH tended to drift. The DC response was subtracted from the EMI data by zeroing the sensor time series before and after the sweeping pattern over the anomaly. As an example, the top plot in

Figure 6-1 was zeroed by subtracting the mean value in the region around 600 samples. At the start and stop of this plot, the sensor value was high due to a small amount of metal on the tripod. The peaks in between are signal from the buried object as the sensor was swept over it.

On the first day of the test, it was observed that the TEM-HH was dropping out large sections of data on most of the files. A day and a half was spent trying to diagnose and fix this. The problem was narrowed down to the backpack electronics used with the TEM-HH. The only quick fix was to replace this backpack with the larger backpack used with the 2X2 TEM array. This fix was implemented on the second day and the entire test site was measured using it. After the test was over, it was discovered that there was a time varying background when the larger, 2X2 backpack was used. Careful comparison of sweeps over the two IVS items (lower two plots in

Figure 6-1) revealed that the levels varied with the direction of the sweep. One item in the IVS was buried to the right of the tripod and one was buried to the left. Sweeps for one item started left to right and for the other started right to left. This is illustrated in

Figure 6-2. Some of this sweeping motion is accomplished by the operator walking, but it is also done by moving the sensor with the arms. When the coil is swept far to the left, it is significantly closer to the backpack than when it is far to the right. With the large backpack, this motion produced a signal shift in the early time gates between 0.5 and 1.0 mV. This shift was enough to result in poorer fits on items with peak signals up to 30-40 mV. A great deal of the small UXO and small clutter were in this amplitude range. To correct for this, it was necessary to select out each background region between the sweeps and interpolate a time varying background. This interpolated, time varying background was subtracted off of the entire signal pattern. This greatly improved the inversion results for peak signals greater than 5-10 mV. Inversion results with weaker signals could not be relied upon. A simple fix for future operations would be to have the second operator wear the backpack and stand by the tripod. There is sufficient cabling for the primary operator to walk forward only with the TEM-coil/SAINT part of the system.

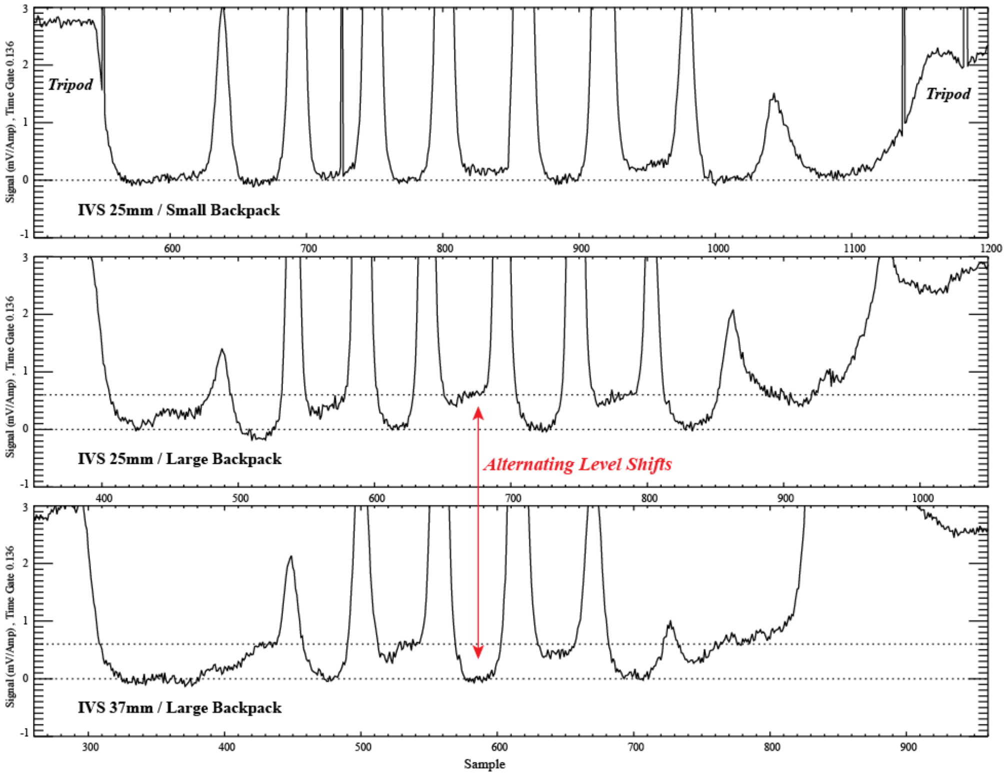

Figure 6-1 – Changing background levels due to large backpack.

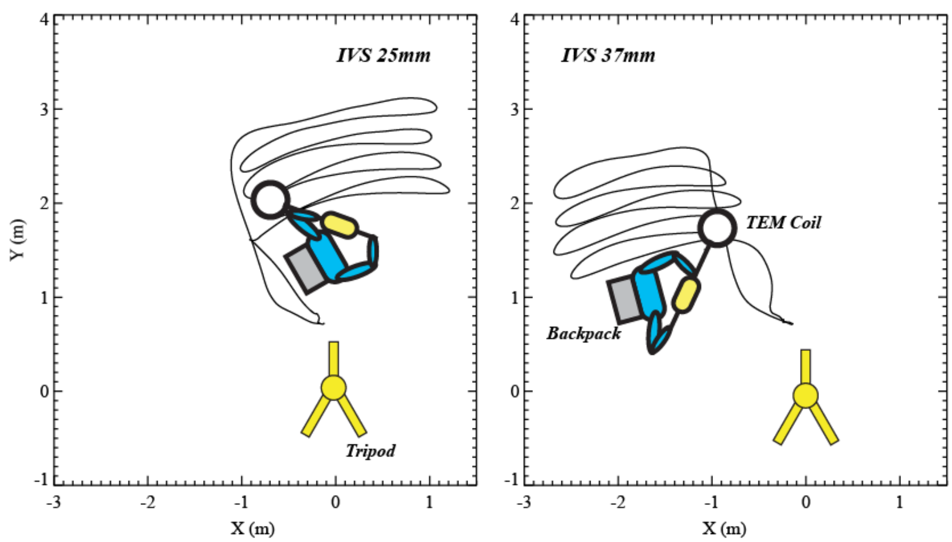

Figure 6-2 – Schematic of coil position relative to backpack

The SAINT IMU data was processed into positions and orientations with an interactive program. The binary file was selected and read in, the IMU data plotted, the zero velocity update regions are selected. There can be multiple sets of sensor sweeps in a single file, but this was not done

for this demonstration. The data was then integrated into trajectories, plotted, and dumped into an ASCII file. The analyst then decided if the position data was good or not. Because there is only one set of sweeps per file, this step could be significantly speeded up if the software had a batch mode that simply ran for multiple files and dumped out data quality plots. The only major problem observed in the data quality plots during this step was an apparent spike in the measured accelerations and a wildly incorrect sensor trajectory. This was occurring on 10-20% of the SAINT measurements. This problem has been observed before. There appears to be an intermittent glitch in the data acquisition of the SAINT that needs to be diagnosed and fixed. For this demonstration, the measurements were simply re-done.

The EMI data was collected at the rate of the total bipolar pulse duration of 1/30th of a second and this was used to time stamp the data. The IMU data was collected at a rate of 600 samples per second and this provided the time stamp for the positioning data. Each data set was collected and time stamped separately. Because the data collection was of short duration, there was no significant drift between the two clocks. The data was approximately synchronized by comparing the back and forth of IMU calculated position to the rise and fall of the EMI data. The EMI inversion model included a time shift as one of the fit parameters to adjust between the two sets of data (EMI and positioning). When there were multiple targets present in the sweep region, synchronizing the SAINT and TEM data became problematic. It was not always obvious how to match them up. There is a fair amount of small debris present on the APG and Blind grids and some of the data could not be processed because of this issue. Synchronizing the two data sets up in hardware would solve this.

6.2 TARGET SELECTION FOR DETECTION

While the APG test grids do not involve a general detection survey where targets must be picked, one still must decide at each grid location whether or not an item is present. Of the 400 flags on the Blind grid, only 298 were visited by the TEM-HH/SAINT based on the detections of past systems. At the flags visited, detection was based on seeing a repeated pattern of peaks as the sensor is swept back and forth. These peaks had to be: above the noise (~0.2 mV), noticeably different from the time varying signal from the large backpack, match up to the timing of the positioning data, and not be on the edge of the sweep region. There was roughly 90 measured locations where no signal was observed. A small fraction of these were large, deep targets that the TEM 5X5 array is better suited to detecting. The rest involved very small scattered debris that the swept EM61-HH detected but the swept TEM-HH did not. A fair portion of detected, small debris was not centered over the sweep region, and it was decided to call these locations empty.

6.3 PARAMETER ESTIMATION

The raw signature data from the TEM-HH sensor reflect details of the sensor/target geometry as well as inherent EMI response characteristics of the targets themselves. In order to separate out the intrinsic target response properties from sensor/target geometry effects we invert the signature data to estimate principal axis magnetic polarizabilities for the targets. The TEM data are inverted using the standard induced dipole response model wherein the effect of eddy

currents set up in the target by the primary field is represented by a set of three orthogonal magnetic dipoles at the target location.

Given a set of measurements of the target response with varying geometries or "look angles" at the target, the data can be inverted to determine the local (X, Y, Z) location of the target, the orientation of its principal axes (ϕ, θ, ψ), and the principal axis polarizabilities (β_1, β_2, β_3). The inversion algorithm is broken into two parts, a non-linear search for (X,Y,Z) and a linear inversion for the polarization matrix. Once the best (X,Y,Z) is found, the polarization matrix is diagonalized for the principle polarizations and orientation angles. Because there is no synchronization between the TEM-HH and the SAINT positioning, there is an added fit parameter to adjust the timing between the two. As long as the back and forth sweeps were roughly lined up in time with the correct TEM-HH peaks, the inversion algorithm smoothly converged to an accurate time shift between the two. Hardware synchronization would eliminate the need for this parameter. The SAINT only calculates a localized coordinate system relative to the tripod location and magnetic north. Because of this, the inverted target location and orientation are not geo-referenced.

It has been noted in the past with the EM61-HH (with SAINT and with template) and with the TEM-HH/template that inversions from measurements made with a single, coaxial transmit/receive coil pair do not always converge to the correct axisymmetric solution for the polarizations. The best match of data to the model is a non-axisymmetric solution. Because of this, the data was inverted two ways: once to find the best match (minimum chi-squared parameter) and once to find the best axisymmetric solution (minimum "cylindrical" parameter). Both inversion results were checked to identify TOI's. Figure 6-3 shows an example of this for the 37mm in the IVS. The left three plots show the chi-squared value, the cylindrical symmetry parameter and the three polarizations in the 0.277 msec time gate as a function of the fit depth parameter. The symmetry parameter is just the difference of the two secondary polarizations divided by the primary polarization. The primary polarization is plotted in black and the secondary's are red and green. The right two plots show the polarizations as a function of time gate at the two different minimums. Underneath this are the inversions parameters for each. There is a 0.03 m difference in the fit depths.

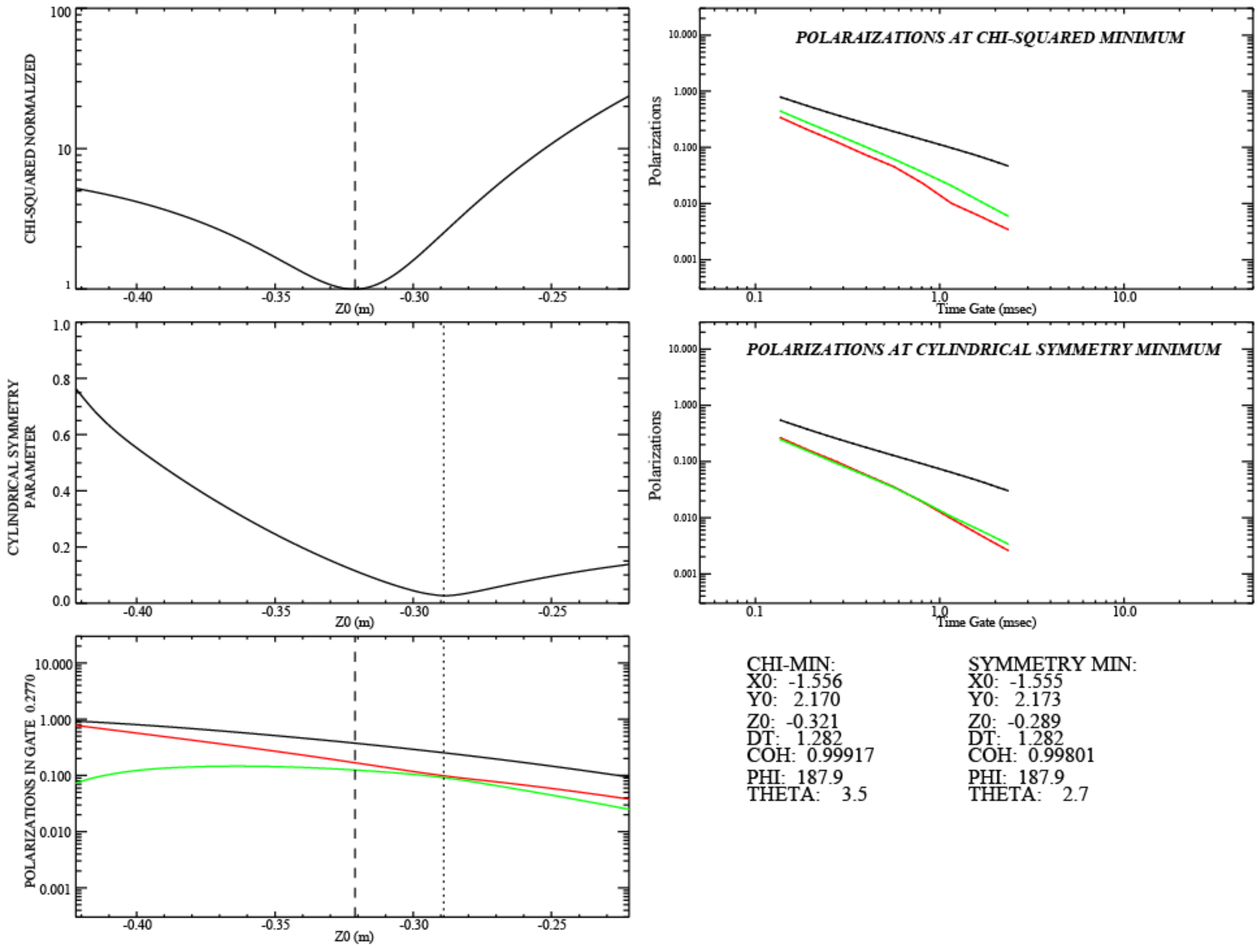

Figure 6-3 – Minimum chi-squared fit versus axisymmetric fit for 37mm in IVS.

To validate this, we have looked at the distribution of polarizations returned by these two fit methods over a common set of objects. If the item is axisymmetric, the minimized cylindrical symmetry parameter returns a tighter distribution of polarizations. Figure 6-4 shows the inverted polarizations for all of the measurements of the two IVS items, a 25mm and a 37mm. There were seven measurements made of each item over 2.5 days. The primary polarizations are black and the secondary's red/green. The solutions on the left plots are at the best model/data match (minimum chi-squared). The solutions on the right are from the best cylindrical symmetry solution. The second set display a more consistent result.

Instruments with multiple transmit/receive pairs with either varying transmit orientations or non-coaxial transmit/receives do not appear to have this convergence problem. Adding several more receive coils to the TEM-HH could solve this problem. The original backpack has an additional two channels available for receive coils. The 2X2 backpack has enough channels for 12 receive coils. It is thought that only a few well-placed receive coils would improve convergence and keep the TEM-HH reasonably light weight. This is discussed further in section 0.

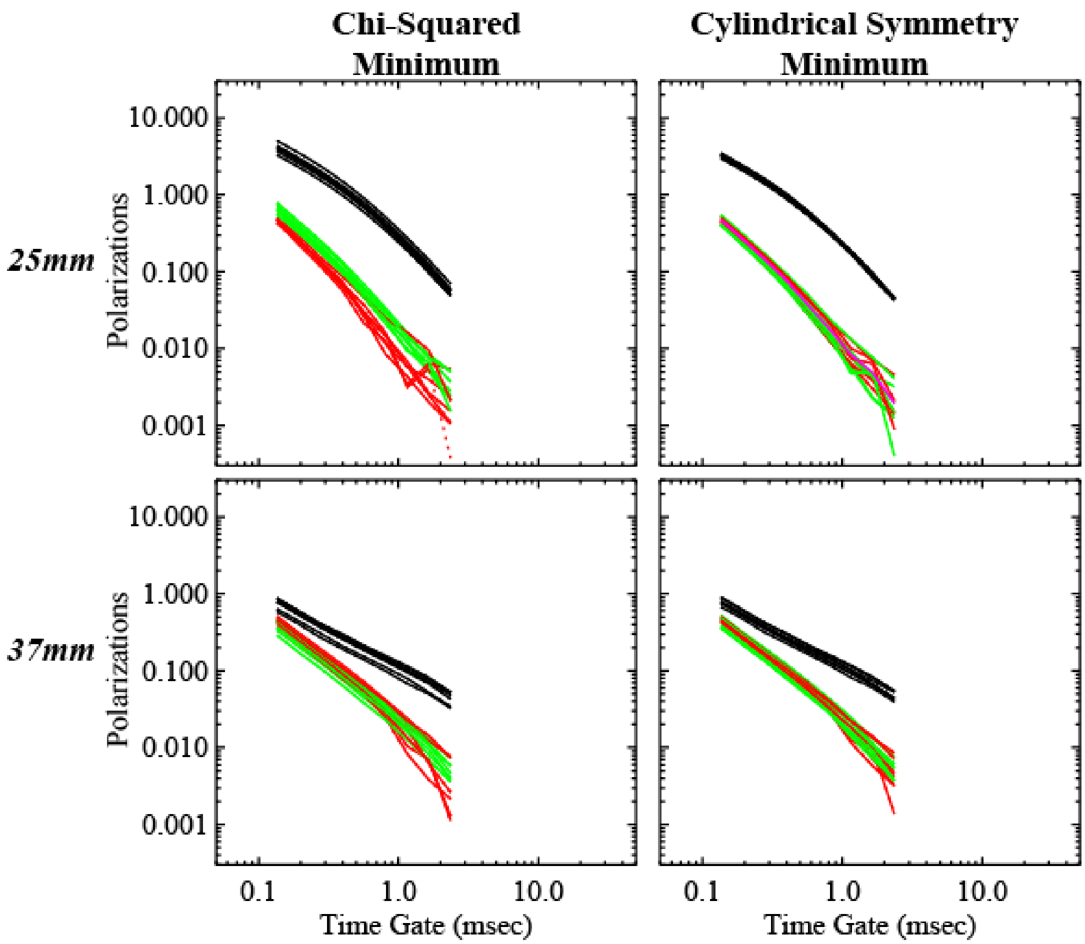

Figure 6-4 – Comparison of inverted polarizations for 25mm and 37mm IVS measurements.

Not every target measured had a strong enough TEM response to support extraction of target polarizabilities. All of the data was run through the inversion routines, and the results were manually screened to identify those targets that could not be reliably parameterized. Several criteria were used in this process: signal strength relative to background, dipole fit error (difference between data and model fit to data), and the visual appearance of the polarizability curves.

Inversion results from multiple source anomalies could not be relied on either. For multiple targets with significant overlap, this is due to a lack of multiple transmit/receive pairs as found on the larger arrays. At APG, most multiple target locations are due to small, spurious debris items and the signals are only partially overlapped. TEM-HH/SAINT data from these items can probably be inverted with an N-dipole algorithm. However, without synchronization of TEM and position data, it was hard to determine how the multiple peaks should mapped out. Because of this, no effort was put into fitting multiple targets.

6.4 CLASSIFICATION

Target classification was based on a library matching procedure wherein we compare the resultant principal axis polarizabilities from a dipole fit to the TEM sensor data for each anomaly to those in a known signature library. This direct comparison method was used to make decisions based on how closely a given set of polarizabilities match a library. We compared the inversion results to the library in three passes and ranked the items in the target list based on the pass. On the first pass, we looked for a close match in all three polarizations. In the second pass, we looked for a close a match in the primary and one secondary. In the last pass, we looked for a close a match only in the primary. All remaining items were labeled as clutter. Items where the inverted polarizations were considered unreliable due to low SNR, multiple targets, or data problems were called "Can't Analyze" and ranked at the very beginning of the target list. Target locations where nothing was detected were ranked at the very end.

6.5 TRAINING

We collected training data in air for the six standard APG ordnance targets (25mm, 37mm, 105mm and 105mm HEAT projectiles, 60mm and 81mm mortars) that are emplaced in the Blind Grid Area with the TEM-HH/SAINT system. These data were used for the fit library entries. This library has been done previously for the stationary TEMTADS array systems using 25-ms pulse duration. The polarizations for most of these items changed for the shorter pulse duration that we used with the TEM-HH/SAINT system. Many of the targets are composites of two or more distinct parts, like a steel body combined with an aluminum tail assembly. Depending on the distance between the sensors and the target, such items can exhibit a range of slightly different EMI signatures corresponding to excitation from different directions. We included measurements with the target oriented nose up, nose down, horizontal and tilted 45 degrees.

Our experience at our Blossom Point test site has been that polarizabilities determined from in-air measurements are indistinguishable from those determined from measurements taken over buried targets. We used data from the calibration lanes, which contain several instances of each target, to establish that this holds true at APG for this sensor system. No differences from in air results were observed.

6.6 DATA PRODUCT SPECIFICATION

The standard reporting template for the Blind Grid (shown below in Figure 6-5) was used to create the target list. The metrics in Section 3.0 were calculated directly from the Scoring Report provided by the Standardized Test Site administrators. The peak signal measured was used for the Response Stage value. Because we did not try to detect items in every cell, but only visited the cells where items had previously been detected, we did not report a response stage value. The Discrimination Stage Ranking was based on the three pass matching discussed above. Classification and Type was determined from the library matching procedure. Depth and Dip values come from the dipole inversion results. Azimuth is not well geo-referenced for this system, but can be estimated based on the orientation of the Blind Grid Area if the orientation of the local SAINT positioning is matched to the grid.

BLIND TEST GRID									
	Letter	Number	Response Stage	Discrimination Stage/Ranking	Classification (Use B for Blank)	TYPE	Depth (M)	Azimuth (Degrees)	Dip (Degress)
1	A	1							
2	A	2							
3	A	3							
4	A	4							
5	A	5							
6	A	6							
7	A	7							
8	A	8							
...	...	...							

Figure 6-5 – Reporting Template for APG Blind Grid.

7.0 PERFORMANCE ASSESSMENT

7.1 INSTRUMENT VERIFICATION STRIP

A 25mm and 37mm projectile were buried roughly 0.30 m deep in the APG test pit. Each was oriented horizontally with one E-W and one N-S. The SAINT tripod was positioned to the south in between the two items. The tripod position was marked with flags to help with re-positioning. The TEM-HH/SAINT system was swept in an E-W pattern over each. Over 2.5 days, each item was measured seven times. The maximum variation in the inverted fit depths was on the order of 6% of the average fit depth. The inverted polarizations for each IVS item are plotted in Figure 7-1. The primary values are black, the secondary's red/green. The dashed magenta curves plot out ±20% of the average amplitude.

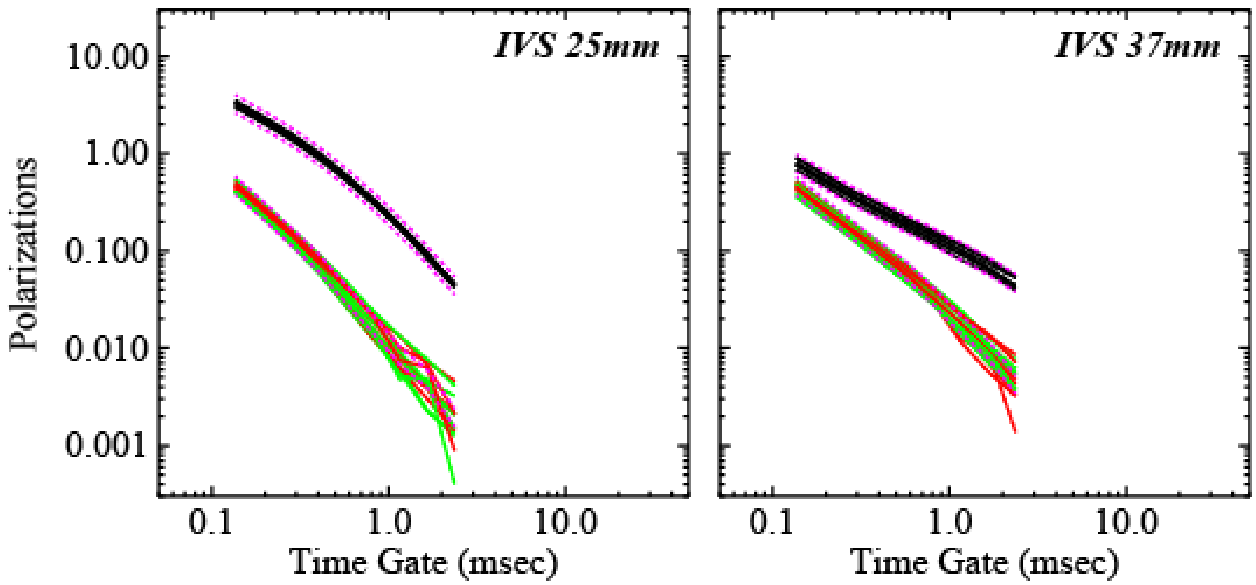

Figure 7-1 – Inverted polarizations from IVS items.

7.2 CORRECT CLASSIFICATION OF TARGETS OF INTEREST

A preliminary ROC curve for the TEM-HH/SAINT is shown in Figure 7-2 (lower, right plot). The same Blind grid, ROC curves for prior TEM systems are also shown. These systems are: the TEM 5X5 array, the EM61-HH/SAINT, and the TEM-HH with template. The full scoring reports for the prior systems can be found on the APG website, [4, 5, 8].

The blue curves are for the discrimination stage scores. The red curves are for detection (called response stage by the APG scorers). For the blue discrimination curves, the x-axis plots the percentage of emplaced clutter counted as one goes through the ranked target list (labeled as probability of false positive). The y-axis plots the percentage of emplaced ordnance counted in

the ranked target list (labeled as probability of detection). No count is made of clutter that is not emplaced, but it is known to exist. The black horizontal line marks the analyst's decision point in the target list to stop digging and everything else should be clutter; this is called the operator's threshold. Table 7-1 compares the discrimination statistics at the operator threshold for the four systems.

All of the systems identified either 96 or 97 percent of the emplaced ordnance at the operator's threshold. The ROC curves reach 1.0 only at the very end of the target ranking. This indicates that the remaining 3% of the ordnance were not detected; these target locations were labeled as empty. These numbers are broken down by ordnance size ranges, and it is the larger and presumably deeper TOI's that are not being detected and identified.

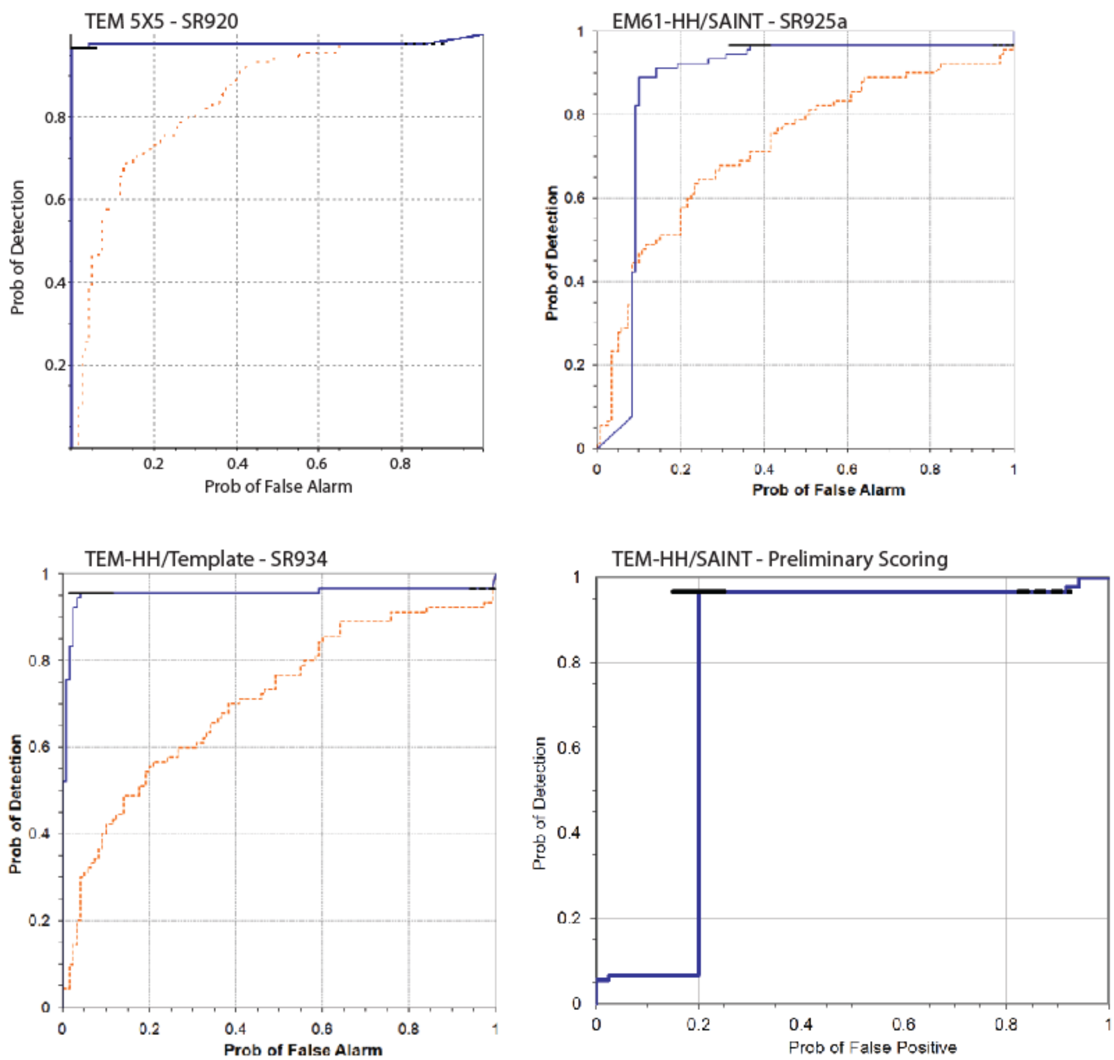

Figure 7-2 – Comparison of discrimination stage ROC curves from APG.

Table 7-1 Comparison of APG Blind Grid Results at Operator's Threshold

	Ordnance - $P_{discriminate}$			
	All Types	**105-mm**	**81/60-mm**	**37/25-mm**
TEM 5X5	0.97	0.93	0.97	1.00
TEM-HH, template	0.96	0.90	0.97	1.00
EM61-HH, SAINT	0.97	0.93	0.97	1.00
TEM-HH, SAINT	0.97	0.93	0.97	1.00
	Clutter - $P_{falsepositive}$			
	All Mass	**0-0.25 kg**	**0.25-1 kg**	**1-10 kg**
TEM 5X5	0.01	0.02	0.00	0.00
TEM-HH, template	0.07	0.03	0.02	0.50
EM61-HH, SAINT	0.37	0.16	0.52	0.80
TEM-HH, SAINT	0.20	0.31	0.12	0.00

7.3 REDUCTION OF FALSE ALARMS

The difference between the four systems is in how well they could reject clutter at the operator's threshold. Both the EM61-HH/SAINT and the TEM-HH/SAINT did not reject as much clutter as the other two systems. In both cases, this was because of the number of items that the analyst determined the systems could not reliably analyze. There were 37 target locations labeled as "Can't Analyze" by the TEM-HH/SAINT system. Roughly half had low SNR and half involved multiple targets. These were ranked first in the dig list. Based on the ROC curve, it appears that most of these items were clutter and probably one TOI. Despite the large number of "Can't Analyze", the system still rejected 80% of the emplaced clutter and exceeded the minimum requirement of rejecting at least 50%.

The EM61-HH/SAINT had a large number of "Can't Analyze" targets as well. Both of these systems were collecting a high density of data points as they were swept low over the ground. This makes them more likely to detect the spurious, small debris on the field which resulted in flag locations with multiple targets. The 5X5 and TEM-HH/template collected sparser data and were higher above the ground.

While not rejecting as much clutter as the 5X5, it should be noted that the TEM-HH/SAINT ROC curve goes directly up after the "Can't Analyze" ranking in the target list. The EM61-HH/SAINT curve is slightly rounded at the top portion of this section. This is presumably the result of having fewer time gates to discriminate with. The TEM-HH/template has a slight trend in this section; possibly because it lacks the higher data density. The 5X5 array has the advantage of multiple, non-coaxial receive coils for each transmit and high SNR signals from averaging.

With modest improvements, it is thought that the TEM-HH/SAINT system could greatly reduce the number of "Can't Analyze" items. Part of the noise problem is the time varying signal from the backpack. This can be fixed by keeping the backpack away from the swept coil and/or using the smaller backpack (after repairs). Adding several receive coils would improve the inversions of low SNR data and may also allow for fitting data with overlapping target signals.

7.4 CUED PRODUCTION RATE

After some initial problems, we were able to visit on average about 27 flag locations an hour and over 200 locations in an eight hour day. A typical day involved an hour break for lunch and 10-15 minute data downloads every hour. After the first day and a half of diagnosing and fixing the system, we were able to measure the Calibration Grid and Blind Grid (364 locations) in a little over 2 days.

Because of an intermittently recurring glitch in the SAINT data collection, roughly 10-20% of the locations had to be re-done. Because of this, the completion rate was roughly 160/day. If the SAINT glitch were fixed, one would realistically expect a comparable rate in a real field where the anomaly locations are not laid out in a nice grid.

7.5 ANALYSIS TIME

On site, the first day and a half was spent diagnosing large drop outs in the TEM-HH data. The problem was determined to be in the small backpack electronics. After replacing this with the larger 2X2 backpack, the drop out problem went away. The rest of the time onsite, the data processing plots and inversion results looked reasonable. After the test, further analysis found poor inversion results for items with peak signals in the 5 to 50 milli-volt range. On close inspection, a time varying background level of 0.5-1 mV was found to be caused by the sweeping motion of the sensor relative to the large backpack. An interactive routine was developed to subtract this background off. This was discussed in Section 6.1. Because of this, post-test analysis took much longer than expected. Time spent post-test per anomaly was probably more in the range of 10-15 minutes.

In any future work, we would change the operation to keep the backpack away from the moving sensor head. This would simplify the background subtraction and keep the analysis time short. Another bottleneck in processing the data was the pre-processing program for the SAINT data. It is set up to run on one file at a time; a batch processing mode for many files would speed things up. If the two data streams were time synchronized in hardware, this would eliminate another step for the analyst. Lastly, because the single transmit/receive pair data does not always

converge well to the correct polarization solution, it is thought that adding several more receive coils may fix this. This would eliminate another step in the processing. Overall, the processing could be done in less than 5 minutes per anomaly, but it did not happen for this test.

7.6 EASE OF USE

Overall, the system was easy to use. The operator carrying the backpack and sweeping the sensor was doing the most physical labor. This operator would switch places with the data analyst every several hours or at lunch. The second operator keeping notes and running the TEM-HH acquisition typically would keep this position all day with breaks for data downloads and lunch. It is thought that switching the backpack to this operator would be a more even division of labor and solve the drifting background issue.

Minor ergonomic adjustments could probably be made to the pole holding the SAINT and coil. An adjustable shoulder strap might place more of the weight on the operator's shoulders than his arms. The operator grasps the pole by its end and by a handle on the SAINT. Being able to adjust this distance for different sized operators may be advantageous.

7.7 RELIABILITY

The first day and a half was spent diagnosing and fixing a problem with the backpack electronics. It was dropping out sections of data. The problem had not been encountered previously, including in last minute test data taken the week before. The final solution was to use the newer set of electronics in the larger backpack which led to another issue already discussed. The two backpacks use similar sets of components and software. It has not yet been determined what is wrong with the older set. For future work, we may just continue to use the newer electronics. This has the added advantage of more data channels and the potential to add several more receive coils.

As already mentioned, the SAINT system has an intermittent glitch occurring in its data files (roughly 10-20% of the time). If the SAINT is used further and adapted to provide time synching with the TEM-HH, this issue should be addressed as well.

Despite these problems, the rest of the system and processing ran well and consistently. The complete site was measured in a little over 2 days.

7.8 ADDING ADDITIONAL RECEIVERS TO TEM-HH

It has been discussed that adding more receivers would improve the inversion process for the TEM-HH. Related fit convergence issues were found with the first 2X2 TEM array with only single Z component receivers. A careful study found that centered, three axis receiver cubes would solve the problem for the 2X2. With the TEM-HH, the questions arises as to whether additional horizontal components at the transmit center or horizontal components outside of the center would be more effective. The goal is to keep the number of receivers to a minimum; such that, the sensor remains truly "hand held." As an initial estimate, we ran simulated fits using one

of 37mm sweeps that did not converge well (see Section 6.3). We ran the forward model with this sweep pattern for three different sensor configurations: the standard, single receiver TEM-HH, a three component cube receiver TEM-HH, and a TEM-HH with the centered z-component and two horizontal- radial receivers. Both of the modeled receiver coil configurations could be implemented in hardware without making the system unwieldy for a hand held sensor. The additional receiver coils are expected to add less than 0.5 pound, resulting in a combined sensor head weight of less than 4 pounds. By comparison, the EM61-HH weights approximately 4 pounds and the MPV weighs 12 pounds. For the radial receiver configuration, the receivers were positioned 12.5cm outside of the transmit loop, which could easily be accommodated by a slightly larger frame.

To evaluate performance, we use the chi-squared error of the fit as a function of fit depth. Diagrams of the three sensors and the resulting plot are shown in Figure 7-3. Generally, the steeper the chi-squared curve, the better the inversion converge. The radial receive configuration is the best solution.

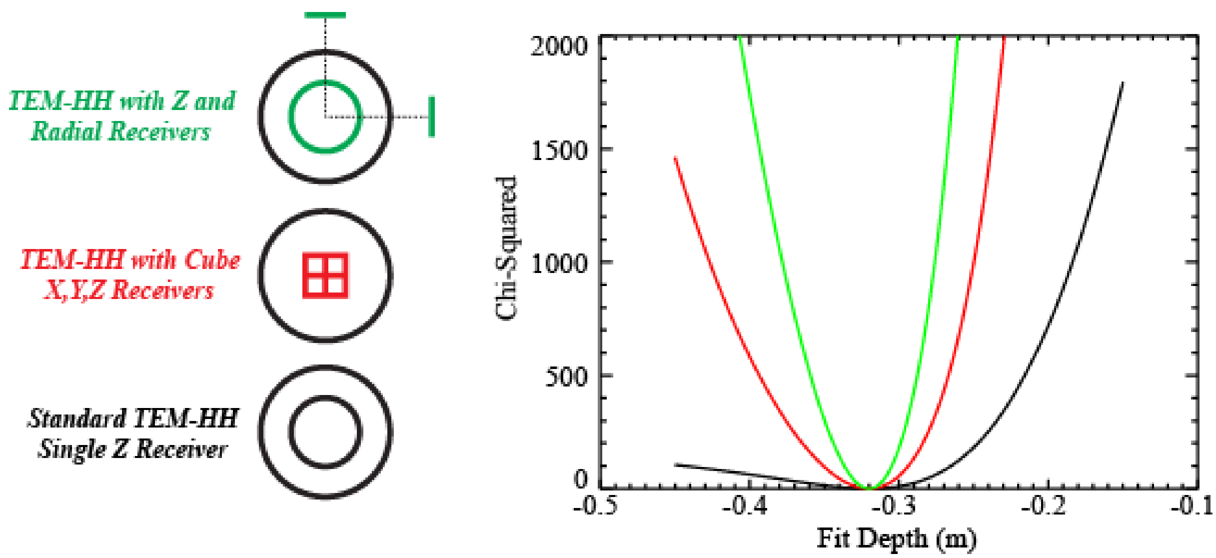

Figure 7-3 – Fit convergence for different TEM-HH receive coil configurations.

7.9 COMPARISON OF DEPLOYING SAINT VERSUS A BEACON SYSTEM

A competing system was developed by Cold Regions Research and Engineering Laboratory in support of SERDP Munitions Response (MR) Project MR-1443 [9]. Their system, which is named the Man Portable Vector EMI sensor, or MPV, combines an EMI sensor, consisting of a 50-cm diameter transmitter loop and an array of five three dimensional receivers, with a dedicated, local, portable positioning receiver station that monitors the primary transmitter field—like a beacon—and returns relative location estimates with cm-level accuracy out to a range of 4 m.

The system was deployed at two test sites in 2012 by Sky Research, Inc. in support of ESTCP MR-201005 [10]. As demonstrated, the MPV sensor head weighs 12 pounds and the backpack-mounted acquisition computer and batteries weigh 35-40 pounds (Figure 7-4).

A reported production rate of 100 targets per day was achieved for the MPV at Yuma Proving Ground and 90 targets per day at Camp Beale. By comparison, the SAINT-aided TEM-HH sensor achieved production rates of nearly 200 per day. It is important to remember, however, that the demonstrations of the SAINT aided TEM-HH and the Beacon-aided MPV were conducted at sites with different deployment conditions and settings. The time required process the SAINT- and Beacon-spatial data appears to be comparable.

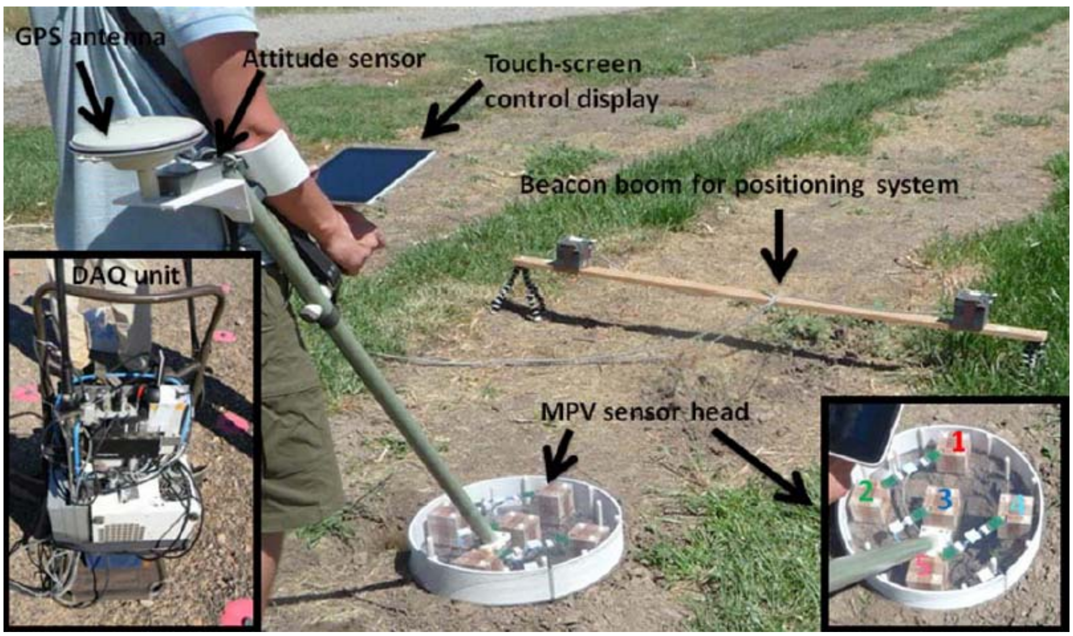

Figure 7-4 – photograph of the MPV sensor and beacon positioning system. The sensor head weighs 12 pounds and the backpack-mounted acquisition computer and batteries weigh 35-40 pounds.

8.0 COST ASSESSMENT

8.1 COST MODEL

The cost elements that were tracked for this APG demonstration are detailed in Table 8-1. The provided cost elements are based on a model used for previous TEM system visits to APG [2]. The model assumes a two-person field crew and one data analyst. Production rates from the APG demonstration of this system were incorporated. While the system is not currently commercially available, an estimated daily rental rate is provided for comparison to other technologies. The rental rate is based, in part, on the costs of items purchased in prototype quantities (single units) and would presumably decrease significantly if the items were procured at production quantity levels.

8.2 COST DRIVERS

Two factors were expected to be strong drivers of cost for this technology as demonstrated. The first is the number of anomalies which can be surveyed per day. Higher productivity in data collection equates to more anomalies investigated for a given period of time in the field. The time required for analyzing individual anomalies can be significantly higher than for other, more traditional methods and could become a cost driver due to the time involvement. The thoughtful use of available automation techniques for individual anomaly analysis with operator QC support can moderate this effect.

8.3 COST BENEFIT

The main benefit to using a UXO classification process is cost-related. The ability to reduce the number of non-hazardous items that have to be dug or have to be dug as presumptively-hazardous items directly reduces the cost of a remediation effort. The additional information for anomaly classification provided by this sensor system provides additional information for the purposes of anomaly classification. If there is buy-in from the stakeholders to use these techniques, this information can be used to reduce costs.

Table 8-1 – TEM-HH/SAINT Tracked Costs

Cost Element	Data Tracked	Cost
Data Collection Costs		
Pre/Post Survey Activities	Component costs and integration costs • Spares and repairs	$3,500
	Cost to pack the array and equipment, mobilize to the site, and return • Personnel required to pack • Packing hours • Personnel to mobilize	$2,000 1 4 1
	Cost to assemble the system, perform initial calibration tests • Personnel required • Hours required	$195 3 0.5
Survey Costs	Unit cost per anomaly investigated. This was calculated as daily survey costs divided by the number of anomalies investigated per day. • Equipment Rental (day) • Daily calibration (hours) • Survey personnel required • Survey hours per day • Daily equipment break-down and storage (hours)	**$7/anom.** $145 0.2 3 8 0.5
Processing Costs		**$22/anomaly.**
Preprocessing	Time required to perform standard data clean up and geophysical data QC.	10 min/anom.
Parameter Estimation	Time required to extract parameters for each anomaly.	2 min/anom.

9.0 IMPLEMENTATION ISSUES

The goal of this demonstration was to show that the TEM-HH combined with SAINT positioning could provide UXO classification performance comparable to the TEM 5x5 array and 2x2 array. Overall, this goal was met. There were several issues noted that should be addressed before trying to use this system at any future ESTCP Munitions Response Live Site Demonstrations.

The SAINT system would require several fixes/improvements. The intermittent data acquisition glitch mentioned in section 7.4 would need to be fixed. A batch processing mode is needed. Finally, some means of time synchronizing its data with the TEM-HH needs to be implemented. All of these would allow for rapid acquisition and analysis of the data.

For the TEM-HH, the small backpack electronics should be repaired. Additional receive coils should be studied and the best (fewest coils / unambiguous inversion) configuration implemented.

Given these updates, we feel that the TEM-HH combined with SAINT positioning is a viable system for cued UXO characterization and would be ready for testing on Live Sites under more rigorous terrain conditions.

10.0 REFERENCE

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APPENDIX – POINTS OF CONTACT

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